

## NON-VOLATILE SEMICONDUCTOR MEMORY DEVICE

### CROSS-REFERENCE TO RELATED APPLICATION

This application is based on and claims the benefit of priority from the prior Japanese Patent Application

5 No. 2000-376501, filed on December 11, 2000, the entire contents of which are incorporated herein by reference.

### BACKGROUND OF THE INVENTION

#### Field of the Invention

This invention relates to non-volatile electrically  
10 rewritable or "reprogrammable" semiconductor memory devices. More particularly, but not exclusively, the invention relates to electrically erasable and programmable read only memory devices.

#### Description of the Related Art

15 Electrically erasable programmable read only memories (EEPROMs) are arranged to include an array of memory cells, each of which typically has a transistor structure with a floating gate for electrical carrier retention and a control gate as insulatively stacked or "multilayered" over the  
20 floating gate. This memory cell is designed to exhibit a threshold voltage-increased state with electrons injected into the floating gate and a threshold voltage-decreased state with the floating gate electrons released away, which are used for storage of binary digital data bits of a logic  
25 "1" and a "0," respectively. The memory cell's data may be read out by first giving a read voltage to the control gate thereof and then detecting or sensing whether this cell

turns on (called "on-cell") to pull a current thereinto or alternatively is kept turned off (called "off-cell").

Currently available sense amplifiers for memory cell data detection include current-sensing amplifiers. Typically a sense amplifier has a sense node and a reference node. A bit line associated with a selected memory cell is connected to the sense node. Connected to the sense-amp reference node is a reference cell, which permits a reference current for data detection to flow therein. The reference cell is the one that is the same in structure as the EEPROM memory cells. A reference current conducted thereby is typically set at a level that is about one-half of a current of the on-cell. With such an arrangement, the intended data detection is done through comparison of a memory cell current with a current of the reference cell.

EEPROM cells inherently have a variation or deviation in mutual conductance  $g_m$  value, which can occur due to changes in fabrication process parameters. Observing this state with respect to a memory cell current, experimentation results are as shown in Fig. 18. Fig. 18 is a graph showing a relationship of a control gate voltage  $V_{cg}$  and cell current  $I_{cell}$ . Here, there is demonstrated a variation of the cell current  $I_{cell}$  occurring upon application of a read voltage  $V_{read}$  to the control gate of a selected memory cell with its threshold voltage  $V_{th}$ . In a way corresponding to a range of from a maximal mutual conductance value  $g_m(max)$  to a minimal value  $g_m(min)$ , the resultant cell read current

would vary within the range of  $I_{cell(max)}$  to  $I_{cell(min)}$ .

As previously stated, the reference current  $I_{ref}$  of a reference cell as indicated by dotted line in Fig. 18 is set so that it is about half of the on-cell's current. If the  
5 minimal cell current  $I_{cell(min)}$  becomes less than the reference current  $I_{ref}$  due to possible variation of  $g_m$  value, erroneous read can occur. Even where the reference current reduction causes no such read errors, a lengthened time period must be required to execute read due to the fact that  
10 an appreciable difference between the cell current and reference current stays less. This makes it impossible to read data at high speeds.

The above problem becomes more serious in the case of multiple-value data storage architectures with the  
15 capability for storing multiple bits of information on a single memory cell transistor, also known as "multiple-bit-level-per-cell" or "multi-level cell (MLC)" technologies. For instance, a multi-bit-per-cell storage scheme is known which employs memory cells of the same structure as those  
20 used in the case of two-level or "binary" data storage and which precisely controls threshold value distributions in a way as shown in Fig. 19. The multibit scheme as shown herein is aimed at storage of four-value data with voltage levels "00," "01," "10," and "11" in the order that one with  
25 a lower threshold voltage precedes others with higher threshold voltages.

Data "00" is considered equivalent to the state that a

memory cell is at its lowest threshold voltage (called "Vth level" from time to time) with electrons released away from the floating gate thereof—for example, define this as an erase state. In order to write or program data "10" from  
5 this erase state, perform writing of a logic "1" of an upper level bit. To write data "01," execute write of a "1" of lower bit. To write data "11," first write data "01" and then execute "1"-write of upper bit.

Upon execution of the data write or erase operation, a  
10 verify-read operation is to be done for forcing each data bit to fall within a prespecified threshold voltage distribution in a similar way to that in the case of binary data. To guarantee the upper and lower limits of such threshold voltage distribution in accordance with respective  
15 data "00," "01" and "10" of Fig. 19, several read voltages ( $V_{vl0}$ ,  $V_{vu0}$ ), ( $V_{vl1}$ ,  $V_{vu1}$ ), ( $V_{vl2}$ ,  $V_{vu2}$ ) should be required in verify-read events.

The resultant threshold voltage distribution of each data thus guaranteed thereby is as follows. For instance,  
20 in the case of "00," it falls within a range of from 1.5 to 2.5 volts (V). In the case of "01," it ranges from 3.5 to 4.5V. In the case of "10," it is from 5.5 to 6.5V. For "11," 7.7V or more.

In contrast, in normal or ordinary read operations,  
25 read voltages  $V_{read0}$ ,  $V_{read1}$ ,  $V_{read2}$  are used, each of which is potentially set between adjacent ones of respective data's threshold voltage distributions.

To perform such highly precise threshold-voltage distribution control, an increased number of values or levels must be required for the ordinary read and verify-read voltages; in addition, the possible variation/deviation of  $g_m$  values of memory cells stated previously becomes greater in influenceability. This can be said because it is required to set up, at fine intervals with increased precision, the reference current of a reference cell in a way pursuant to each ordinary read voltage and verify-read voltage, which would result in a decrease in allowable deviation range of the cell current  $I_{cell}$  due to a change in  $g_m$  as has been discussed in conjunction with Fig. 18.

And, for preclusion of any read errors, an increase in margin should be required in such a way that a marginal space or "interspace" between respective data threshold voltage distributions is set at 1.5V rather than 1V, by way of example. Unfortunately, such margin expansion in this way can result in an extra increase in the upper limit value of a read voltage(s). This upper-limit value increase causes application of a higher voltage to memory cells once at a time whenever a read operation is executed, which in turn causes EEPROMs to decrease in reliability. Another problem encountered with the approach is a decrease in on-chip net areas for layout of memory cells and associative circuitry. This is resulted from an unwanted increase in chip occupation area of "booster" circuits that are operable to generate any required high potential voltages such as

read voltages or else. Obviously, the greater the requisite number of high voltages, the more the on-chip area of such boosters.

#### SUMMARY OF THE INVENTION

5       A non-volatile semiconductor memory device comprises:  
an array of electrically rewritable or reprogrammable  
nonvolatile data storage memory cells each having a  
transistor structure with a control gate; reference current  
source circuit configured to generate a first reference  
10   current adaptable for use during an ordinary read operation  
and a second reference current for use during a verify-read  
operation for data status verification in one of writing and  
erasing events; a sense amplifier configured to compare read  
currents of a selected memory cell as selected during the  
15   ordinary read operation and the verify-read operation with  
the first and second reference currents respectively to  
thereby perform data detection; and a driver configured to  
give an identical voltage to the control gate of the  
selected memory cell presently selected during the ordinary  
20   read operation and the verify-read operation.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagram showing an arrangement of an EEPROM chip in accordance with one embodiment of this invention.

Fig. 2 is a diagram showing a structure of a memory  
25   cell used in the EEPROM of Fig. 1.

Fig. 3 is a diagram showing a configuration of data read circuitry of the embodiment.

Fig. 4 is a graph for explanation of principles of read and verify-read operations of the embodiment.

Fig. 5 is a pictorial representation for explanation of a read operation of the embodiment.

5 Fig. 6 is a diagram showing major voltage waveforms in a write operation mode of the embodiment.

Fig. 7 is a diagram showing a pattern of threshold voltage distributions after execution of a write operation of the embodiment.

10 Fig. 8 is a diagram showing a configuration of read circuitry of an EEPROM chip in accordance with another embodiment of the invention.

Fig. 9 is a diagram showing a reference current distribution of the embodiment of Fig. 8.

15 Fig. 10 is a diagram showing a configuration of a division converter circuit in Fig. 8.

Fig. 11 is a diagram showing a configuration of read circuitry of an EEPROM chip in accordance with still another embodiment of the invention.

20 Fig. 12 is a diagram showing a reference current distribution of the Fig. 11 embodiment.

Fig. 13 is a diagram showing a configuration of a difference division converter circuit of Fig. 11.

25 Fig. 14 is a diagram showing a configuration of circuitry for measurement of a cell current distribution(s).

Fig. 15 is a graph showing cell current distributions as measured by use of the Fig. 14 circuitry.

Figs. 16 and 17 are diagram each showing a configuration of another circuitry used for cell current distribution measurement.

Fig. 18 is a diagram showing one exemplary cell current distribution in one prior art EEPROM.

Fig. 19 is a graph showing threshold voltage distributions of four-value data.

#### DETAILED DESCRIPTION OF THE EMBODIMENTS

##### First Embodiment

Referring to Fig. 1, there is shown an overall configuration of an electrically erasable programmable read only memory (EEPROM) device in accordance with one embodiment of this invention. The EEPROM shown herein includes an array 1 of rows and columns of memory cells, which are laid out in a matrix form. This memory cell array 1 may be designed so that its arrangement is of any available types including, but not limited to, the NAND type, NOR type, and DINOR type.

A single memory cell of the cell array 1 is structured as shown in Fig. 2. An n-type silicon substrate 11 has a surface region for formation of the memory cell array 1, in which region a p-type well 12 is formed. Over this p-type well 12, a floating gate 16 is formed with a tunnel current-flowable gate insulation film 15 which is interposed between p-well 12 and floating gate 16. A control gate 18 is insulatively stacked or "multilayered" over the floating gate 16 with an interlayer dielectric film 17 laid



therebetween.  $n$  ( $n^+$ ) type impurity-doped layers 13, 14 for use as source and drain are formed in p-well 12 so that these are self-aligned with the overlying control gate 18.

The floating gate 16 is formed of a polycrystalline silicon or "polysilicon" film whereas the control gate 18 is of either polysilicon film or polycide film (multilayer film of polysilicon and metal silicide films). The "intergate" dielectric film 17 lying between the floating gate 16 and control gate 18 is typically formed of an oxide-nitride-oxide (ONO) film, which is a multilayer film of silicon oxides with a silicon nitride sandwiched therebetween. Floating gate 16 has its lateral walls that are normally coated with a protective sidewall film made of silicon nitride or other similar suitable materials.

The floating gate 16 is independent per each memory cell. The control gate 18 is continuously formed to extend along cells in a direction perpendicular to the surface of the drawing paper sheet, for use as one of parallel word lines. The memory cell is covered with an interlayer dielectric film 19. Provided on this film 19 are parallel bit lines crossing over the word lines at virtually right angles thereto, one of which is indicated by numeral 20 in Fig. 2. This bit line 20 is connected to the underlying  $n^+$ -type diffusion layer 13 of the illustrative cell structure.

Selecting of a memory cell from the memory cell array 1 is performed by a row decoder 2 and column decoder 3 plus column gate 3a shown in Fig. 1. While addresses are fetched

into an address register 5 through an input/output (I/O) buffer 8, a row address and a column address involved therein are decoded by the row decoder 2 and column decoder 3, respectively. Row decoder 2 includes a word-line driver operable to give to a selected word line different voltages in accordance with operation modes. A bit line is selectable by column gate 3a as selected in response to an output of column decoder 3.

The circuitry of Fig. 1 also includes a data-sense/data-latch circuit 4, which includes a sense amplifier for detection or sensing of read data and a data latch for holding write data therein. Data writing is done through repeated execution of a write pulse application operation and its following verify-read operation in a way as will be set forth in detail later in the description. Sequence control of this write mode is to be done by a control circuit 6. While erase and verify-read operations are executed during data erasing also where necessary, the control circuit 6 is also responsible for the sequence control of such erase mode.

A variety of kinds of high voltages for use during the write, erase and read operations, which are potentially higher than the EEPROM chip's supply voltage, are generated by a high-voltage generator circuit 7 and then supplied to the row decoder 2 and/or cell array 1 under control of the control circuit 6 in an operation mode-dependent way.

Referring next to Fig. 3, there is depicted a

configuration of main part of data readout circuitry  
operatively responsible for verify-read operations to be  
executed during an ordinary read operation and write  
operation. The circuitry shown herein includes a sense  
5 amplifier 31. This sense amp 31 is configured from an  
operational amplifier OP and a couple of P-channel metal  
oxide semiconductor (PMOS) transistors P0, P1. The op-amp  
OP has input terminals for use as a sense node SN and a  
reference node RN, to which the PMOS transistors P0, P1 are  
10 connected as current source load, respectively. Also  
connected to the sense node SN is a bit line BL as coupled  
to a presently selected memory cell MC in the memory cell  
array 1. The reference node RN is associated with one of  
reference current sources which is connected thereto after  
15 selection by a reference current source circuit 30. This  
reference current source circuit 30 is made up of a  
plurality of reference current sources 32 and a switch  
circuit 33 operable to select one from among these current  
sources 32.

20 The reference current sources 32 are designed to employ  
a plurality of reference cells RC01 to RC03, RC11-RC13 and  
RC21-RC23, which are required for ordinary read and verify-  
read operations. These reference cells RC01-RC23 are  
substantially the same in structure as the memory cells MC.  
25 Prior to detailed explanation of the reference current  
sources 32, the principles of the ordinary read and verify-  
read operations in the illustrative embodiment will first be

set forth with reference to Fig. 4 below. Fig. 4 is a graph demonstrating an experimentation result in the case of four-value data storage per cell by way of example, which graph shows the relationship of a threshold voltage distribution of each data and cell currents as conducted during ordinary-read and verify-read operations. The four-value data storage scheme is also called four-level or four-bit per cell technology.

The 4-data write procedure is the same in principle as the prior art scheme that has been discussed in conjunction with Fig. 19 in the introductory part of the description. More specifically, a data bit with a voltage level "00" is defined to be a state with the lowest threshold voltage. One example is that in "flash" EEPROMs, all the cells in a certain memory block are erased together at a time—known as "all-at-a-time" erase or "all-at-once" erase among those skilled in the flash device art—prior to execution of data writing to thereby establish an erase state of the "00" level. From this erase state, writing of "11," "01" and "10" will be done by execution of bit data writing for one or two times. Data erase is achievable in a way which follows. In the cell structure of Fig. 2, apply between the p-well 12 and control gate 18 a specific high voltage (called an erase voltage) with its polarity made positive on the p-well 12 side, causing residual electrons held on floating gate 16 to release away toward the channel side.

Data writing is executable in a way which follows.

Apply a positive high voltage (write pulse) to the control gate 18 causing the threshold voltage to selectively increase while either permitting or precluding electron injection into the floating gate 16 in accordance with a data potential being presently given to either the drain or channel via a bit line. Practically the write operation is done to finally result in establishment of a prespecified write state through iterative execution of the write pulse applications to the control gate and the verify-read operations in the way as stated previously.

One noticeable feature unique to the illustrative embodiment is that as shown in Fig. 4, a read voltage  $V_{read}$  being given to the memory cell MC's control gate in ordinary read operations is also used with no changes during its following verify-read operation during writing mode. Note here that the read voltage  $V_{read}$  for use during ordinary read operations is common among any data read events irrespective of which one of the four different data bits is to be read. This means that the use of a single read voltage  $V_{read}$  enables accurate determination or "interpretation" of all the data levels "00," "01," "10" and "11."

And, in a verify-read operation with application of such read voltage  $V_{read}$ , several reference current values are set up for the data levels "00," "01" and "10" as available upon application of this read voltage  $V_{read}$  respectively, which are verify-read use reference current

values corresponding to current values almost at the upper and lower limits of the threshold voltage distributions thereof—i.e. Iverify0 (its upper limit is Iverifyl0 and lower limit is Iverifyu0), Iverify1 (with upper limit of Iverifyl1 and lower limit of Iverifyu1), and Iverify2 (with upper limit of Iverifyl2 and lower limit of Iverifyu2).

Regarding the data "00," while its verify operation is an erase-verify operation in the case of the "all-at-once" erasing, if in a verify-read event with application of the read voltage Vread the resulting cell current is affirmed so that it is midway between the upper limit value Iverifyl0 and lower limit value Iverifyu0, then "pass" is established. Similarly in the case of "01" writing, "pass" is set if in a verify-read event with application of the same read voltage Vread the resultant cell current is affirmed to be midway between the upper limit value Iverifyl1 and lower limit value Iverifyu1. In the case of "10" write, "pass" is set if in a verify-read event with application of the same read voltage Vread the resultant cell current is affirmed midway between the upper limit value Iverifyl2 and lower limit value Iverifyu2.

It should be noted that for actually implemented verify check schemes, both of the upper limit value and lower limit value will not necessarily be used as the reference current values required. Either one of these values is solely employable when the need arises.

Also note that the verify-read of data "11" is

achievable by utilization of a method having the steps of giving to the control gate a different voltage from the read voltage Vread, e.g. a verify-read voltage higher in potential than voltage Vread, and then conforming that "off" is presently established.

With execution of the above-stated verify-read operation, this does not result in guarantee of the threshold voltage of data being written as in prior art schemes but results in guarantee of data by a cell current(s) upon application of the read voltage Vread. And in the case of this embodiment, identically the same read voltage Vread is used also in ordinary read operations in a similar way to the verify-read operation. In other words, whereas in the prior art a cell current is read with setup of a read voltage between the threshold value distributions of respective data, the embodiment is such that a single type of read voltage Vread is used to perform the intended determination of "00," "01," "10" and "11" data through comparison with read-use reference current values Iread01, Iread12, Iread23 shown in Fig. 4. The read reference current value Iread01 is set so that it is midway between the verify-read reference current values Iverifyu0 and Iverifyl1. Similarly the read reference current value Iread12 is set to be midway between the verify-read reference current values Iverifyu1 and Iverifyl2. The read reference current value Iread23 is set less than the reference current value Iverifyu2.

With execution of such verify-read operation and ordinary read operation, any replacement or "reversal" between a cell current and reference current value will no longer take place principally even where deviation is found in "gm" values of memory cells concerned. This can be said because any write data is well guaranteed by a cell current at read voltage  $V_{read}$ . Accordingly, read errors may be precluded or at least greatly suppressed, enabling the read operation to be done at high speeds.

The reference current source circuit 30 shown in Fig. 3 is configured from several reference cells RC for use as the current sources for producing and conducting a plurality of reference currents to be used during the above-noted ordinary-read and verify-read operations, respectively. The reference current source 32 of Fig. 3 is exemplarily suited in configuration for the case of four-value data storage per cell as has been discussed in conjunction with Fig. 4. Reference cells RC01, RC02 are for production of reference currents  $I_{verify10}$ ,  $I_{verifyu0}$  to be used during verify-reading for "00" data check. Reference cell RC03 is a current source for generation of reference current  $I_{read01}$  for use during ordinary reading for "00" data check. Reference cells RC11, RC12 are for production of reference currents  $I_{verify11}$ ,  $I_{verifyu1}$  to be used during verify-read for "01" data determination whereas reference cell RC13 is a current source for conducting reference current  $I_{read12}$  as used during ordinary read for "01" data determination.



Reference cells RC21, RC22 are for production of reference currents Iverify12, Iverifyu2 used during verify-read for "10" data determination; reference cell RC23 is a current source for generation of reference current Iread23 to be  
5 used during ordinary read for "10" data interpretation.

These reference cells RC01-RC03, RC11-RC13 and RC21-23 are specifically arranged so that while all of them are the same in structure and size as the memory cells MC, they have carefully adjusted gate threshold voltages which are  
10 different in value from one another to thereby ensure that a respective one of the reference current values as set forth in conjunction with Fig. 4 is obtainable upon application of the read voltage Vread to the control gate of a cell of interest. Their control gates are common-coupled together  
15 to a reference word line RWL. A read voltage same as the read voltage Vread being supplied to a selected word line WL from a word-line driver within the row decoder 2 is to be given to this reference word line RWL during read and verify-read operations.

20 In a verify-read operation, the switch circuit 33 operates to select one from among the verify-read reference cells RC01-RC02, RC11-12, RC21-22 in a way pursuant to write data to be checked, causing the drain of such selected cell to be connected to the reference node RN of sense amplifier  
25 31. Alternatively in an ordinary read operation, switch circuit 33 selects one from among the ordinary read reference cells RC03, RC13, RC23 causing the drain of a

selected one to be coupled to the sense amp 31's reference node RN.

It must be noted that in order to reduce complexities in the procedure for determination of four-value data "00,"  
5 "01," "10," "11," the sense amp 31 is actually designed using a plurality of sense amplifiers for enabling simultaneous selection of the read-use reference currents Iread01, Iread12 and Iread23 to ensure that respective ones are given to different reference nodes. In this respect,  
10 see Fig. 5. This diagram shows a read operation in case three separate sense amps 31a-31c are employed, which operation is for giving to these sense amps the ordinary read reference currents Iread01, Iread12, Iread23 respectively at a time. In this case, data determination or  
15 "interpretation" may be done based on whether the resultant cell current  $I_{cell}$  is larger or smaller in value than which one of the reference currents Iread01-Iread23, in a way which follows. If  $I_{cell} > I_{read01}$ , then outputs of sense amps 31a-31c are all at "0." Thus data "00" is determined.  
20 If  $I_{read01} > I_{cell} > I_{read12}$ , then sense amp 31a's output is at "1" with outputs of the other sense amps 31b-31c set at "0" whereby data "01" is determined. If  $I_{read12} > I_{cell} > I_{read23}$  then outputs of sense amps 31a-b are at "1" with sense amp 31c's output set at "0" so that data "10" is judged. If  
25  $I_{read23} > I_{cell}$  then outputs of sense amps 31a-b are all at "1," permitting determination of data "11."

See Fig. 6, which is a diagram showing a waveform of a

control gate voltage  $V_{cg}$  of a selected memory cell MC in a write mode along with that of a reference cell RC associated therewith. This is an exemplary case where the memory cell MC being presently in the data "00" erase state of Fig. 4  
5 for example is subjected to writing of a logic "1" at its lower bit to thereby write or program "01" data. At this time, the reference cell RC to be selected by the switch circuit 33 is either RC11 or RC12, which has its control gate to which a read voltage  $V_{read}$  identical to that of the  
10 memory cell MC is applied. To the memory cell MC, a write pulse voltage  $V_{pgm}$  and a verify-read voltage  $V_{read}$  are applied repeatedly.

And the write pulse application results in a gradual increase in threshold voltage of the memory cell MC. When a  
15 cell current of memory cell MC upon execution of verify-reading becomes smaller than the reference current  $I_{verify1}$  due to the reference cell RC12 by way of example, an output of the sense amplifier 31 is inverted, leading to a judgment of the termination of a present write event. Whereby the  
20 "01" data write is set at "pass." For guarantee of the lower limit of a threshold voltage distribution of "01" data (actually a corresponding cell current), it is required that the reference cell RC11 be used to also execute verify check at reference current  $I_{verify11}$ .

25 In the case of writing or erasing other data "00" and "10" also, a similar operation is done with a mere difference of the reference cell RC to be selected—i.e. a

similar verify-read is executed while giving the read voltage  $V_{read}$  to reference cell RC. As per the "11" data, a verify-read voltage different from the read voltage  $V_{read}$  is used in the way stated supra.

5        With the write operation of this embodiment, since the verify read is executed for guarantee of the resultant cell current, it is very likely that the actually written data's threshold voltage distribution expands to have a greater spreadability than is possible with the prior art. An  
10        experimentation result concerning this is shown in Fig. 7. In view of the fact that a certain data state is guaranteed by a reference current value  $I_{verifyA}$ , a threshold voltage distribution of this data state must accompany a deviation of the  $g_m$  value of a memory cell between the case of its  
15        minimal value  $g_m(\min)$  and the case of a maximal value  $g_m(\max)$ , which deviation is within a range of from  $V_{th1}$  to  $V_{th2}$  as shown in Fig. 7. Accordingly, the data state that is guaranteed by a reference current value  $I_{verifyB}$  less  
20        than the reference current value  $I_{verifyA}$  will possibly experience overlapping of neighboring data's threshold voltage distributions as indicated by broken lines in Fig. 7.

      Fortunately the presence of this threshold value distribution overlap state hardly causes any appreciable read errors. This can be said due to the following reason.  
25        Whereas the reference current  $I_{verifyA}$  is used during verify-read with application of the read voltage  $V_{read}$ , ordinary read with the use of the same read voltage  $V_{read}$  is

executed in a way such that a cell current is to be read at the reference current value  $I_{readA}$  that is lower than the value of verify-read reference current  $I_{verifyA}$ . As far as this reference current value  $I_{readA}$  is set intermediate  
5 between the verify-read reference current values  $I_{verifyA}$  and  $I_{verifyB}$ , data with guarantee by the reference current value  $I_{verifyA}$  is successfully read without regard to any resultant threshold voltage distributions.

#### Second Embodiment

10 In Fig. 4, several reference cells RC similar in structure to the memory cells MC are prepared for use as the reference current sources 32 in a way corresponding to the requisite number of reference current values concerned. This approach is modifiable so that a single "basic"  
15 reference cell RC is prepared while arranging the reference current source circuit to produce a plurality of other reference currents based on this single reference cell. Fig. 8 shows, in a way corresponding to that of Fig. 3, a configuration of a second embodiment having a reference  
20 current source circuit 71 with such an arrangement.

The reference current source circuit 71 of this embodiment is designed to employ a single reference cell RC0 which conducts a reference current  $I_0$  upon application of a read voltage  $V_{read}$  to the control gate thereof. And a  
25 division converter circuit 72 is provided for production of a plurality of reference currents  $I_0/a$ ,  $I_0/b$ , ..., which are subdivided from the reference current value  $I_0$  by positive

numbers "a," "b," ..., respectively. The illustrative circuitry includes an NMOS transistor QN0 connected to the reference node RN of a sense amplifier 31, which is arranged so that a voltage V0 is given to the gate causing a  
5 reference current as selected by the division converter circuit 72 to flow in the NMOS transistor QN0.

A configuration of the division converter circuit 72 is shown in Fig. 10. As shown herein, this circuit includes a PMOS transistor QP0 for use as a current source load and a  
10 "basic" reference cell RC0, which make up a reference current circuit 721. The reference cell RC0 is similar in structure to memory cells MC. When giving the read voltage Vread to its control gate, a current I0 rushes to flow. This reference current circuit 721 is operatively associated  
15 with a predetermined number, n, of multiple PMOS transistors QP11, QP12, ..., QP1n for use as current sources, which constitute a current mirror circuit 722 together with the PMOS transistor QP0. These current-source PMOS transistors QP11-QP1n are specifically designed so that their channel  
20 widths measure W/a, W/b, ..., respectively, where "W" is the channel width of PMOS transistor QP0. This is under an assumption that all the PMOS transistors QP11-1n are identically the same in channel length as PMOS transistor QP0.

25 With such channel-width/channel-length settings, the PMOS transistors QP11, QP12, ..., QP1n serve as the intended current sources for permitting flow of reference currents

$I_{0/a}$ ,  $I_{0/b}$ , ..., respectively. These will be used as respective reference current sources  $I_{verify}$  for verify-reading and reference current sources  $I_{read}$  for ordinary read in the previous embodiment. These PMOS transistors  
5 QP11-QP1n are such that their sources are connected to the power supply VCC through activation switches SW1, SW2, ..., SWn respectively, with their drains connected together to a diode-coupled NMOS transistor QN1.

This NMOS transistor QN1 is an output transistor for  
10 execution of current-to-voltage conversion, in which transistor a reference current  $I_{0/x}$  flows. This current is determinable by one of the PMOS transistors Qp11-1n as selected by switch SW1, SW2, .... This NMOS transistor QN1's drain voltage  $V_0$  is given to the gate of NMOS transistor QN0,  
15 which is connected to the reference node RN of sense amplifier 31. These NMOS transistors QN0, QN1 also make up a current mirror circuit. Assuming that these are the same in size as each other, a reference current  $I_{0/x}$  is expected to flow in NMOS transistor QN0.

20 This embodiment thus arranged is capable of generating a plurality of ordinary-read reference currents and verify-read reference currents through subdivision of the reference current  $I_0$  that is determinable by the basic reference cell RC0. And, in a similar way to that in the previous  
25 embodiment, any required reference current may be selected by a switch in a way conformity with an ordinary-read operation and verify-read operation. Very importantly, the

same read voltage  $V_{read}$  is given to the control gate of such reference cell  $RC0$  during both of the verify-read and ordinary read operations, whereby the cell current-guaranteed write is executed based on the same principles as  
5 the previous embodiment.

It should be noted that although the example of Fig. 9 is drawn to the case of setup of a current division ratio " $x$ " ( $=a, b, \dots$ ) at 1 or greater, i.e., sequential decrement of  $I0/a, I0/b, \dots$  with the original reference current  $I0$   
10 being as a maximal value, the ratio  $x$  may alternatively be set less than 1. In other words, production of a reference current or currents greater than the reference current  $I0$  is also permissible. One practical example is that the inherently original reference current value  $I0$  is set at an  
15 intermediate level between many required reference current values while setting the current division ratio  $x$  to permit creation of other reference current values at upper and lower levels thereof.

An advantage of this embodiment lies in an ability to  
20 reduce complexities in the manufacture or fabrication of the reference current source circuitry, when compared to the case of formation of a great number of size-different reference cells  $RC$  with complicated structures similar to the memory cells  $MC$  as in the previous embodiment.

### 25 Third Embodiment

The second embodiment discussed above is such that the reference cell consists of a single cell  $RC0$ , whose



reference current is divided into current components or "segments" for production of a plurality of reference currents required. Due to this, simple current division can result in lack of guarantee of the minimal reference current value  $I_{read23}$  as has been explained in conjunction with Fig. 4. The minimum value of reference current  $I_{read23}$  is not a mere read-use reference current but the one that offers a capability to guarantee the availability of the minimum read current of a cell. The reason for this is as follows. For instance, in the case of NOR type Flash EEPROMs with an increased number of memory cells being parallel-connected to each bit line, leakage currents of multiple non-selected cells can overlap or "superpose" the current of a selected cell. Thus, any accurate data determination is no longer executable in the state that the current of on-cell is less than a total sum of leakage currents.

To avoid this, the illustrative embodiment is specifically arranged to make use of at least two reference cells for enabling guarantee of the minimum read current value stated supra. One such circuit configuration is shown in Fig. 11 in a way corresponding to that of Fig. 8. A reference current source circuit 101 shown herein comes with a couple of reference cells RCA and RCB, wherein the former cell exhibits a current value  $I_A$  when applying the read voltage  $V_{read}$  to the control gate thereof whereas the latter has a current value  $I_B$  upon application of read voltage

Vread to its control gate. Here, the value  $I_A$  is greater than  $I_B$ . The reference cell RCB is for guarantee of the minimum reference current. And a difference division converter circuit 102 is provided for generation of several  
5 reference current values  $(I_A - I_B)/a$ ,  $(I_A - I_B)/b$ , ... falling within a range defined by the minimum current value  $I_B$  and maximum current value  $I_A$ . A respective one of these current values is equal to a difference between the current values  $I_B$  and  $I_A$  divided by a positive number "a," "b," ....

10 The circuitry of Fig. 11 includes a sense amplifier 31 having its reference node  $R_N$ , to which a parallel combination of two NMOS transistors  $Q_{NA}$ ,  $Q_{NB}$  is connected. The NMOS transistor  $Q_{NB}$  is the one that guarantees the minimum read current. More specifically the difference  
15 division converter circuit 102 for driving NMOS transistors  $Q_{NA}$ ,  $Q_{NB}$  is arranged to ensure that the minimum current  $I_B$  determinable by the reference cell RCB flows in NMOS transistor  $Q_{NB}$  while at the same time permitting flow in NMOS transistor  $Q_{NA}$  of a reference current as divided by the  
20 difference division converter circuit 102 to have a value of  $(I_A - I_B)/x$ .

A practically reduced configuration of the difference division converter circuit 102 is shown in Fig. 13. This circuit includes two, first and second reference current  
25 circuits 201 and 202. The first reference current circuit 201 is made up from a single reference cell RCA and a PMOS transistor  $Q_{P0}$  for use as a current source. The second

circuit 202 is formed of another reference cell RCB and current-source PMOS transistor QP22. The reference cells RCA, RCB used herein are virtually the same in structure as the memory cells MC. Each reference cell RCA, RCB is  
5 carefully adjusted in threshold voltage, causing a current  $I_A$ ,  $I_B$  to flow therein upon application of the read voltage  $V_{read}$  to the control gate thereof.

The PMOS transistor QP22 of second reference current circuit 202 is operatively associated with a PMOS transistor  
10 QP23, which makes up a current mirror circuit together with transistor QP22. PMOS transistor QP23 permits a current  $I_B$  to flow in a diode-coupled NMOS transistor QN2. NMOS transistor QN2 is the one that converts the current into a corresponding voltage. Its drain voltage  $V_b$  is to be  
15 supplied to the gate of one NMOS transistor QNB being connected to the sense-amp reference node RN. Supposing that NMOS transistors QNB and QN2 are the same in size as each other, the current  $I_B$  must flow in NMOS transistor QNB.

The Fig. 13 circuitry also includes another PMOS  
20 transistor QP21, which constitutes a current mirror together with the PMOS transistor QP22 of second reference current circuit 202. PMOS transistor QP21 permits the current  $I_B$  to be fed also to the reference cell RCA of first reference current circuit 201. This in turn forces a specific current  
25 with its value equivalent to a difference between the two reference current values, i.e. value  $I_A - I_B$ , to flow into the load PMOS transistor QP0 of first reference current circuit

201.

The first reference current circuit 201 is operatively associated with a plurality of,  $n$ , PMOS transistors QP11, QP12, ..., QP1n, which make up a current mirror circuit 203  
5 together with the PMOS transistor QP0. These PMOS transistors QP11-QP1n are designed in on-chip dimensions so that their channel widths are sequentially set at "W/a," "W/b," ..., respectively, where W is the channel width of PMOS transistor QP0. Assume here that these are the same in  
10 channel length as PMOS transistor QP0.

With such an arrangement, the PMOS transistors QP11-QP1n act as current sources for permitting flow of reference currents with values of  $(I_A - I_B)/a$ ,  $(I_A - I_B)/b$ , ..., respectively. These are to be used as respective reference  
15 current sources  $I_{\text{verify}}$  during verify-read and respective reference current sources  $I_{\text{read}}$  during ordinary read in the embodiments discussed previously. PMOS transistors QP11-1n are such that their sources are connected to the power supply VCC through activating switches SW1, SW2, ..., SWn  
20 respectively whereas drains are common-connected together to a diode-coupled NMOS transistor QN1.

Thereby obtained at the NMOS transistor QN1 are a plurality of ordinary read-use reference currents and verify-read use reference currents  $(I_A - I_B)/x$ , which are  
25 determinable by PMOS transistors QP11, QP12, ..., QP1n as selected by the switches SW1, SW2, ..., SWn. This NMOS transistor QN1's drain voltage  $V_a$  is given to the gate of

another NMOS transistor QNA being connected to the reference node RN of comparator 31. Assuming that NMOS transistors QNA, QN1 are the same in size as each other, the same current as QN1 is expected to flow in NMOS transistor QNA.

5        It has been stated that with this embodiment, the reference current on the reference node RN side has a specific value equivalent to a sum of a division of a difference between two reference current values IA and IB, i.e.  $(IA-IB)/x$ , and the minimum current value IB while  
10        guaranteeing such minimum current value IB. Consequently as in the prior embodiments, the reference current selected by activation switch is obtainable in response to a present operation mode, which in turn makes it possible to execute write in such a way that data is guaranteed by a read  
15        current while at the same time reliably assuring the availability of a minimal read current required.

      It should be noted that although in the above example two reference cells are used to establish the range for current division, the difference division converter circuit  
20        may alternatively be modified so that three or more reference cells are employed for subdivision of the cell current range into a plurality of sub-ranges to thereby permit generation of a difference current value in each of these subranges.

25        In the embodiments stated above, the more than one reference cell RC is arranged to be the same in structure as the memory cells MC. This is due to some reasons.

Principally the reference current or currents may also be created by use of presently existing standard transistors. However, this approach does not come without accompanying a penalty which follows: in cases where the memory cells MC of memory cell array 1 decrease in the average  $g_m$  value due to possible deviation in fabrication process parameters or the like, the distribution of "00" data of Fig. 4 can sometimes "override" the state of negative threshold voltage when executing verify-read with a reference current value while referring to a certain transistor as fabricated through different processes from memory cells MC. This would result in an unwanted increase in current leakage at non-select cells during ordinary read operations, which in turn leads to an inability to execute normal read in any way. On the contrary, if the reference current source is configured from a reference cell(s) RC being the same in structure as the memory cells MC, then the above-noted problem is avoidable because of the fact that the reference cell or cells RC may well reflect any possible variation or deviation in the average cell characteristics of a chip.

An explanation will next be given of a method for checking the data write (or erase) state of a memory cell as has been programmed in the foregoing embodiments discussed above. Traditionally such write data check is done through measurement of a threshold voltage distribution(s). In this case, a control voltage is externally given to the gate of a memory cell MC while letting a check current level be kept

constant; then, let a specific control voltage value at which the memory cell MC changes from turn-on to off be set at a gate threshold voltage of such memory cell. In contrast, with the EEPROM in accordance with this invention is such that as has been set forth in conjunction with each embodiment stated supra, memory cell data must experience the write-verify read for guarantee of a cell current; additionally, as previously stated using Fig. 7, any possible threshold voltage distribution overlap or superposition is made acceptable between neighboring data items. As a consequence, risks of data verify/check incapacibilities can occur even upon execution of the threshold voltage distribution measurement that is similar to the prior art.

#### Fourth Embodiment

To avoid the problem above, a fourth embodiment of this invention is arranged to perform cell current distribution measurement for write data state check. More specifically as shown in Fig. 14, an EEPROM chip is provided with an external connection pad 301, to which an external reference current source 302 is connected. The external current source connection pad 301 is to be connected to the reference node RN of a sense amplifier 31. This sense amp 31 has its sense node SN as coupled to selected memory cell MC via a bit line BL. A read voltage  $V_{read}$  is applied to word line WL connected to the control gate of the memory cell MC. And the value of a current of such external

reference current source 302 is scanned to monitor or "watchdog" a specific current value at which an output of sense amp 31 attempts to invert.

Whereby, as shown in Fig. 15, cell current distribution patterns corresponding to four-value data are thus obtained. In Fig. 15, such 4-value data's threshold voltage distributions are indicated by solid lines whereas cell current distribution patterns available upon reading of "00," "01," "10" data with the read voltage  $V_{read}$  are indicated by dotted lines. Regarding "11" data, any appreciable cell current no longer flows during application of the read voltage  $V_{read}$  so that no current distributions are obtainable; and, no needs arise to do so. While the graph of Fig. 15 demonstrates threshold voltage distribution patterns without accompanying any overlap or superposition between neighboring data distributions, the cell current distributions indicated by dotted lines will hardly overlap each other as far as data write is completed successfully. This is true even when the threshold voltage distributions could overlap each other as stated previously.

#### Fifth Embodiment

Turning to Fig. 16, there is shown on-chip circuitry in accordance with a fifth embodiment of the invention, with the cell current distribution measurement scheme of Fig. 14 being modified. In this case the external reference current source 302 to be connected to the reference current source pad 301 is fixed. This chip involves a built-in reference



current generator circuit 304 operable to generate a reference current for distribution draw-up/formulation, which has its value equal to a current value of this external reference current source 302 divided by a number "z," where z is positive, and then couple it to the reference node RN of sense amplifier 31. And an external control signal pad 303 is provided for receipt of an external control signal as used to appropriately control this reference current generator circuit 304.

10       The reference current generator circuit 304 is configurable from circuitry employing a current mirror circuit for generating a plurality of reference currents at certain subdivision ratio in a similar way in principle to that of the reference current source circuit 71 used in the Fig. 8 embodiment stated supra.

15       With the use of such cell current distribution measurement scheme, it is no longer required to change or modify the inherent current value of the external reference current source 302, which in turn makes it possible to lighten the burden or load of externally associated measurement equipment or instrument.

#### Sixth Embodiment

25       Turning next to Fig. 17, there is shown circuitry with another cell current distribution measurement scheme in accordance with a sixth embodiment of the invention. As shown herein, a reference transistor 305 for use during distribution measurement is provided, which has a drain

connected to the reference node RN of sense amplifier 31, a source coupled to ground, and a gate connected to an external voltage source pad 306. Preferably the distribution measuring reference transistor 305 is a  
5 reference cell similar in structure to the memory cells MC of EEPROM chip. Pad 306 is connected to an external reference voltage source 307 operatively associated therewith.

In this arrangement, scan a voltage of the external  
10 reference voltage source 307. Then, let the scanned voltage be subject to voltage-current conversion at the distribution measuring reference transistor 305 for monitoring of a certain voltage value whereat the sense-amp 31's output inverts. Supposing that the voltage-versus-current  
15 characteristics of distribution measuring reference transistor 305 are known in advance, it is possible to obtain the intended cell current distribution of write (or erase) data as discussed in conjunction with Fig. 15.

Although the above embodiments are directed to the case  
20 of multi-value data storage per cell, this invention should not exclusively be limited thereto and may also be applicable successfully to two-value or binary data storage architectures. In the case of 2-value data storage, a logic "1" data state with higher threshold voltage and a "0" data  
25 state with lower threshold voltage are typically employed. A read voltage used in this case is potentially set to be midway between the "0" and "1" data's threshold voltage

distributions. In case "0"-data write is executed with the "1" data regarded as an erase state, prior art EEPROMs are designed to execute cell's turn-on/off determination in a write-verify read mode by use of a read voltage lower in  
5 potential than a read voltage used during ordinary reading. The illustrative embodiment, by contrast, is such that the same read voltage as that during ordinary read is used in verify-read cycles also—in a similar way to that of the embodiments with 4-value storage scheme stated supra—to  
10 thereby execute write with increased or maximized cell current guarantee. This enables successful execution of write under no influence of the *gm* values of the memory cell MC.